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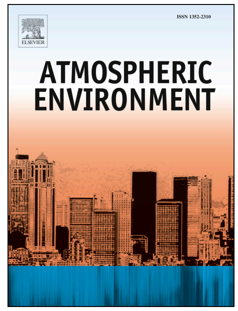


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**C. D. Desouza:** writing original draft, writing review and editing, methodology, software, formal analysis, investigation, data curation, visualisation

**D. J. Marsh:** Funding acquisition, conceptualisation, writing review and editing

**S. D. Beevers:** Writing review and editing, validation

**N. Molden:** Resources, funding acquisition, writing review and editing

**D. C. Green:** Conceptualisation, data curation, writing review and editing, visualisation, supervision

# Real-world emissions from non-road mobile machinery in London

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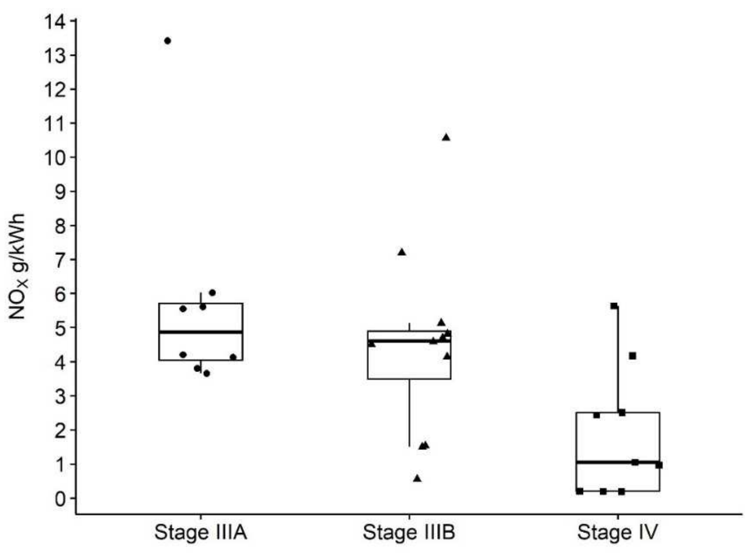
## Abstract

The 2016 London atmospheric emissions inventory estimates that, the construction sector contributes 34% of the total $PM_{10}$ and 7% of the total $NO_X$ – the largest and 5th largest sources, respectively. Recent on-road light duty diesel vehicle emission tests have shown significant differences between real-world $NO_X$ emissions compared with results from laboratory based regulatory tests. The aim of this study was therefore to quantify the 'real-world' tail-pipe $NO_X$, $CO_2$, and particle emissions, for 30 of the most commonly used construction machines in London under normal working conditions. The highest $NO_X$ emissions (g/kWh) were from the

older engines (Stage III-A ~4.88 g/kWh and III-B ~4.61 g/kWh), these were reduced significantly (~78%) in the newer (Stage IV ~1.05 g/kWh) engines due to more advanced engine management systems and exhaust after treatment. One Stage IV machine emitted $NO_X$ similar to a Stage III-B machine, the failure of this SCR was only detectable using PEMS as no warning was given by the machine. Higher $NO_X$ conformity factors were observed for Stage IV machines, due to the lower $NO_X$ emission standards, which these machines must adhere to. On average, Stage III-B machines (~525 g/kWh) emitted the lowest levels of $CO_2$ emissions, compared to Stage III-A (~875 g/kWh) and Stage IV (~575 g/kWh) machines. Overall, a statistically significant (~41%) decrease was observed in the $CO_2$ emissions (g/kWh) between Stage III-A and III-B

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machines, while no statistically significant difference was found between Stage III-B and IV machines. Particle mass measurements, which were only measured from generators, showed that generators of all engine sizes were within their respective Stage III-A emissions standards. A 95% reduction in $NO_X$ and 2 orders of magnitude reduction in particle number was observed for a SCR-DPF retrofitted generator, compared to the same generator prior to exhaust gas after-treatment strategy.

**Highlights**

- $NO_X$, $CO_2$, and particulate exhaust emissions from a total of 30 construction machines, including 9 different types, were measured using UN-ECE R-49 compliant, portable emissions measurement system (PEMS).
- The PEMS measurements were carried out on active construction sites in London, giving an indication of 'real-world' emissions.
- Measured $NO_X$ emissions indicate that approximately 75% of the machines tested conform to within a factor of 2.1.

**Keywords:**

Non-road mobile machinery

real-world emissions

portable emissions measurement systems

UN-ECE R-49 compliant PEMS

$NO_X$ conformity factors



# 1 Introduction

Both internationally [1] and in the UK [2], air pollution is one of the largest environmental public health risks. In 2012, the World Health Organization classified diesel engine exhaust as carcinogenic to humans, based on evidence that exposure was associated with an increased risk of lung cancer [3]. Air pollutants include, but are not limited to ozone ($O_3$), nitrogen oxides ($NO_X$), sulphur dioxide ($SO_2$), carbon monoxide (CO), particulate matter (PM), hydrocarbons (HC), and metallic pollutants. In London, the major sources of $NO_X$ and PM emissions are road transport (primarily diesel fuelled), domestic and commercial gas combustion, industry, non-road mobile machinery (NRMM), aviation, and resuspension [4]. In 2016, the construction sector was estimated to contribute to 15% of the total $PM_{2.5}$ – the 3rd largest source, 34% of the total $PM_{10}$ – the largest source (includes fugitive dust and diesel exhaust), 7% of the total $NO_X$ – 5th largest source, and 1% of the total $CO_2$ of emissions in London [4].

NRMM is defined as any mobile machine, transportable equipment or vehicle, with or without bodywork or wheels, not intended for the transport of passengers or goods on roads, and includes machinery installed on the chassis of vehicles intended for the transport of passengers on roads [5]. Quantifying the in-use emission factors of these machines is more challenging than on-road vehicles, due to complex duty cycles and the wide range of activities undertaken. Many researchers have carried out portable emissions measurement systems (PEMS) tests on various types of NRMM [6, 7, 8, 9, 10, 11, 12], including generators [13], excavators [14], backhoes, wheel-loaders, bulldozers, motor graders using laboratory grade and regulatory compliant [15] equipment. Johnson et al. [6] evaluated the in-use emission factors from 27 different pieces of construction equipment and Frey et al. [8] reported on the real-world duty cycles for construction equipment. Several studies have also been conducted using non-compliant PEMS equipment [10, 16, 17, 18]. Due to the continuous development of PEMS [19] and the European standards for in-use service compliance and monitoring testing for Stage V non-road engines [20], improving these approaches is a high priority [21].

Johnson et al. [6] recognise that NRMM engines have relatively longer life spans, due to their inherent durability, increasing the impact of this sector beyond what would be experienced in the on-road fleet. The NRMM fleet in London is a good example of this; in 2016, 31% of the registered fleet of NRMM used on construction sites was made up of older machinery: Stages I to III-A [22]. In contrast, in 2016, Euro IV and older diesel HGVs (emission standard introduced in 2005), having a similar $NO_X$ emission standard as Stage III-A NRMM (last emission standard introduced in 2008), made up less than 25% of the total kilometres driven by all diesel HGVs in Inner London. It is therefore critical to reduce the emissions from non-road construction equipment, in the interest of protecting public health. The exhaust emission abatement of on road vehicles is well established through legislation such as EU Directives (e.g. 70/220/EEC) and further emission restrictions in London such as the London Low Emission Zone and the Ultra-Low Emission Zone. However, the emission reduction legislation of NRMM is not so well advanced. To illustrate this, the dates of introduction of EU emission standards for on-road engines (g/km) and off-road engines (g/kWh) are summarised in Figure 1. This illustrates how emissions standards for non-road machines have been introduced later than their heavy-duty on-road engine equivalents. Along with a delay in the introduction of emission standards for NRMM, there is also a leniency in the limit values for the emission standards. During any given year since the introduction of the EU emission standards, on-road heavy-duty diesel and gas engines have had to adhere to tighter $NO_X$ (g/kWh) limit values compared to NRMM engines. For instance, current (2019) and future (2020) EU Stage V $NO_X$ emission standards for a subset of NRMM engines (<56 kW net power and >560 kW net power) are up to an order of magnitude higher than their heavy-duty gas and diesel engine counterparts.

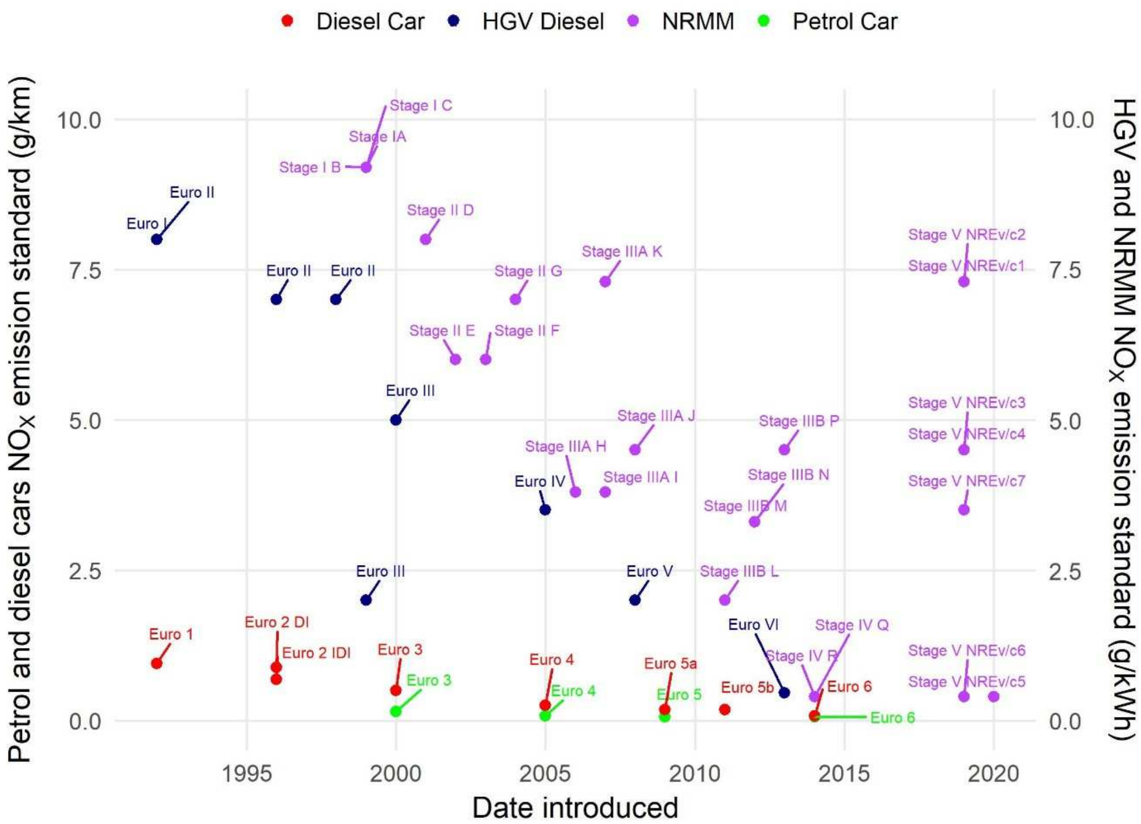



*Figure 1 Timeline schematic showing the introduction of $NO_X$ EU emission standards* for different types of engines.*

**Note: NRMM engines have different emission standards within a Stage; for example, Stage III-B has sub-categories 'L', 'M', 'N', and 'P', which have $NO_X$ emission standards of 2, 3.3, 3.3, and 4.7($NO_X$+HC) g/kWh respectively.*

Due to this lag in the emission standards for the NRMM fleet, the relative contribution of NRMM emissions in London, and elsewhere, is predicted to increase in coming years. This was recognised in London, where the Greater London Authority planning guidance requires larger construction sites to conform to the tighter emission standards across the city, which are stricter in central London [23]. Understanding of emissions from this source and the development of adequate policy interventions to reduce emissions is therefore a high priority. This work aims to provide $NO_X$, PM, and $CO_2$ emission factors for use in an emissions inventory for the construction NRMM fleet in London. Since, governmental policies are focusing on 'zero-tailpipe emissions' for the future, $CO_2$ is reported here instead of CO, despite CO being a criteria pollutant. Currently, there are no emission standards for $CO_2$, for non-road engines.

# 2 Methodology

To maximise the number and type of machines available, and provide diversity in age and in-service use, portable emissions measurement systems (PEMS) measurements were undertaken on active construction sites as well as at dedicated testing facilities. This presented several practical and methodological challenges, which are generally not found in controlled or laboratory environments, thus required the development of new approaches.

## 2.1 Identifying NRMM to test

Planning guidance [23] requires all large construction sites in London to keep a log of the NRMM used on site, which is recorded in a register of construction machinery [24]. The use of the register is enforced by periodic site audits and is therefore an accurate reflection of the fleet, holding detailed information on the NRMM, the start and end dates of construction site projects, machinery deployment duration, site location, NRMM type, engine size, machinery manufacturer, and engine emission standard. The register has been used as part of this study to prioritise the NRMM categories for emission testing. To rank the contribution of each NRMM to emissions in London, the fleet composition was combined with an estimate of activity and the respective EU emission standard limit value for each engine category. Engine activity was assumed to be uniform across the different machine classes (e.g. generators were assumed to run for 24 hours a day, while all other machines were assumed to operate for 8 hours). As the planning guidance currently requires Stage III-B and Stage IV machines to be used in the central London, and by 2020 this will extend to the whole of London [25, 26], newer machines were prioritised for testing. Stage III-B and IV machines were estimated to contribute 61% of current $NO_X$ emissions.

The Stage III-B and Stage IV machines, which contributed more than 1% of the registered fleet are shown in supplementary information. This provided a list of the most significant 29 (Stage III-B and IV) NRMM machine categories to $NO_X$ emissions in London. 22 machines (representing 15 of 29 categories) were tested over a period of 2 years and represented 73% of the estimated $NO_X$ emissions from Stage III-B and Stage IV machines in London. Access to machines of the 14 remaining categories (of 31) could not be achieved (8 of these 14 machines were misclassified on the register, including 3 dumpers, 4 forklifts/telehandlers, and 1 generator). These 13 categories were all ranked below 2% of individual $NO_X$ contribution; together they comprised 27% of estimated emissions in London. Nevertheless, the NRMM reported here represented the majority of the machinery used in London and 45% of estimated $NO_X$ emissions.

Generators are one of the most common machines used on construction sites. In 2016, they made up 5% of the total fleet used in London – the 5$^{th}$ most common type of NRMM. Applications include tower lighting, operating tower cranes, security cameras, electricity for on-site office-cabins, drying rooms, and hand-held power tools. Such a variety of applications imply that generators tend to operate continuously for 24 hours a day. Most sites do not consider generators as 'mobile' and hence fail to register generators on the inventory. Additionally, generators have older engines, currently type approved to meet EU Stage III-A emission standards in London. Therefore, generators do not appear on the list of rank classified NRMM. The engines in generators, have no exhaust gas after-treatment to control for $NO_X$ or particulate emissions; hence, when operated continuously, they have a significant impact on the overall emissions at any site.

The technical specifications and activities performed by the machines tested are shown in Table 1. Standard red diesel (ULSD, sulphur content < 15 ppm) was used in all machines, as per governmental regulations. Details on the emission factors for individual activities for each NRMM are shown in supplementary information.

*Table 1 Technical specifications, activities performed, measured $NO_X$ emission factors, $NO_X$ limit value of the respective emission standard, and calculated $NO_X$ conformity factors for the NRMM tested.*

| **NRMM Type** | **Engine size (kW)** | **Engine model year** | **Engine hours** | **EU emission standard** | **Activity performed** | **Measured $NO_X$ (g/h)** | | | **Calculated $NO_X$ (g/kWh)** | **$NO_X$ limit value (g/kWh)** | **$NO_X$ conformity factor** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | **Cold start** | **Idle** | **Average working activity** | | | |
| Generator | 48kW | 2013 | 5882 | III-A | 25-100% engine load | N/A‡ | N/A | 93.47 | 4.2 | 4.5 | 0.93 |
| Excavator | 49kW | 2015 | 3482 | III-B | moving, digging, lorry-loading | 39.85 | 29.29 | 97.13 | 4.58 | 4.5 | 1.02 |
| Dumper | 55kW | 2015 | 218 | III-B | moving, dumping, lorry loading-unloading | 109.87 | 53.39 | 163.07 | 7.19 | 4.5 | 1.6 |
| Dumper | 55kW | 2015 | 923 | III-B | moving, dumping, lorry loading-unloading | 125.35 | 44.57 | 79.92 | 5.13 | 4.5 | 1.14 |
| Forklift | 55kW | 2017 | 9 | III-B | moving, lifting | 119.52 | 74.74 | 262.06 | 10.56 | 4.5 | 2.35 |
| Telehandler | 55kW | 2017 | 636 | III-B | moving, lifting, material re-handling | 77.4 | 46.08 | 40.77 | 4.51 | 4.5 | 1 |
| Generator | 64kW | 2011 | 4654 | III-A | 10-100% engine load | N/A | N/A | 166.27 | 5.61 | 4.5 | 1.25 |
| Excavator | 73kW | 2014 | 5898 | III-B | moving, digging, lorry-loading, lifting | 177.77 | 48.67 | 115.75 | 4.63 | 3.3 | 1.4 |

‡ N/A: cold start and idle emissions not recorded for all generators

| NRMM Type | Engine size (kW) | Engine model year | Engine hours | EU emission standard | Activity performed | Measured $NO_X$ (g/h) | | | Calculated $NO_X$ (g/kWh) | $NO_X$ limit value (g/kWh) | $NO_X$ conformity factor |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Cold start | Idle | Average working activity | | | |
| Excavator | 78kW | 2017 | 2113 | IV | moving, digging, lorry-loading | 65.66 | 41.04 | 9.36 | 2.51 | 0.4 | 6.27 |
| Generator | 80kW | 2015 | 1962 | III-A | 10-100% engine load | N/A | N/A | 140.86 | 3.8 | 3.8 | 1 |
| Telehandler | 81kW | 2013 | 1578 | III-B | moving, material re-handling, lifting | 67.75 | 55.33 | 151.81 | 4.81 | 3.3 | 1.46 |
| Excavator | 93kW | 2017 | 1104 | IV | moving, digging, grading | N/A[§] | N/A | 7.32 | 5.63 | 0.4 | 14.07 |
| Telehandler | 93kW | 2014 | 738 | IV | moving, material re-handling | 146.38 | 83.2 | 156.25 | 4.17 | 0.4 | 10.42 |
| Generator | 100kW | 2015 | 2201 | III-A | 10-100% engine load | N/A | N/A | 168.99 | 3.65 | 3.8 | 0.96 |
| Pump | 112kW | 2004 | N/A | III-A | Pumping | 248.08 | 237.71 | 470.09 | 13.41 | 3.8 | 3.53 |
| Excavator | 129kW | 2013 | 1092 | III-B | moving, trenching, grading, lorry-loading | 98.03 | 97.67 | 182.56 | 4.7 | 3.3 | 1.42 |

[§] N/A: information not recorded; values assumed similar to an engine of the same family and class

| NRMM Type | Engine size (kW) | Engine model year | Engine hours | EU emission standard | Activity performed | Measured $NO_X$ (g/h) | | | Calculated $NO_X$ (g/kWh) | $NO_X$ limit value (g/kWh) | $NO_X$ conformity factor |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Cold start | Idle | Average working activity | | | |
| Excavator | 129kW | 2017 | 1985 | IV | moving, lorry-loading | 100.19 | 68.58 | 1.76 | 2.43 | 0.4 | 6.08 |
| Excavator | 129kW | 2016 | 1704 | IV | moving, digging, lorry-loading, lifting | 120.78 | 2.95 | 0.68 | 0.2 | 0.4 | 0.5 |
| Loader | 136kW | 2016 | 526 | IV | moving, lifting, material re-handling | 101.23 | 2.74 | 4.34 | 0.19 | 0.4 | 0.48 |
| Pump | 150kW | N/A | N/A | III-B | pumping | 157.64 | 74.66 | 303.34 | 4.15 | 2 | 2.08 |
| Generator | 160kW | 2011 | 18708 | III-A | 10-100% engine | N/A | N/A | 305.53 | 4.12 | 3.8 | 1.08 |
| Crane | 186kW | N/A | N/A | III-B | lifting | 72.47 | 46.12 | 80.39 | 1.53 | 2 | 0.77 |
| Generator | 260kW | 2012 | 14878 | III-A | 25-100% engine load | N/A | N/A | 725.45 | 6.02 | 3.8 | 1.58 |
| Generator | 260kW | 2012 | N/A | IV | (retrofit) 25-100% engine load | N/A | N/A | 116.13 | 0.96 | 0.4 | 2.4 |
| Excavator | 317kW | 2011 | 4712 | III-B | lorry-loading | 168.23 | 58.54 | 219.96 | 1.5 | 2 | 0.75 |

| NRMM Type | Engine size (kW) | Engine model year | Engine hours | EU emission standard | Activity performed | Measured $NO_X$ (g/h) | | | Calculated $NO_X$ (g/kWh) | $NO_X$ limit value (g/kWh) | $NO_X$ conformity factor |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Cold start | Idle | Average working activity | | | |
| Rig | 328kW | 2016 | 3402 | IV | drilling | 148.57 | 74.81 | 1.66 | 1.05 | 0.4 | 2.63 |
| Pump | 375kW | 2013 | 1141 | IV | pumping | 192.89 | 2.41 | 49.44 | 0.19 | 0.4 | 0.48 |
| Rig | 382kW | 2014 | 5734 | III-B | drilling | 41.26 | 30.17 | 65.45 | 0.55 | 2 | 0.28 |
| Generator | 400kW | 2014 | 8079 | III-A | 10-75% engine load | N/A | N/A | 1029.11 | 5.55 | 3.8 | 1.46 |

## 2.2 Portable Emission Measurement Systems

Two types of gaseous Portable Emission Measurement Systems (PEMS) were used in this study: SEMTECH®DS (Sensors Inc., US) and SEMTECH®LDV (Sensors Inc., US); both meet UN-ECE R-49 & Commission Regulation (EU) No. 582/2011 in the European Union and 40 CFR part 1065 in the USA. Both PEMS have been maintained and linearized by the manufacturer in the same way and calibrated on the same gas bottles in the field. The PEMS were selected based on availability at the time of testing. The measurement approaches are also common to both systems: non-dispersive ultra-violet ($NO_X$); non-dispersive infra-red (CO and $CO_2$) and flame ionization detector (FID) for total hydrocarbons (THC; not reported in this study). The system collected a sample of raw exhaust gas from the exhaust flow meter (EFM), through a sample line heated to 190°C. This is consistent with the regulations for THC measurement. PM emissions were measured using the Pegasor particle sensor Mi2 (PPS-M, Pegasor Inc., Finland) with sample probe installed downstream of the gaseous sample points. Five different size exhaust flow meters were used, depending on the size of the engine in each machine and exhaust mass flow rate. The entire PEMS equipment was powered by the mains electrical supply where available and battery packs for the mobile measurements. For the generator tests, the PEMS was installed next to the machine and the sample lines and the exhaust flow meter extended out to the exhaust of the generator. For the off-road tests, the PEMS was mounted using the manufacturers' standard vibration-damping plate and covered with a dust-shield.

Quality assurance was ensured by a pre-test calibration after the PEMS was connected on the machine; this included a leak check and zero-span calibration. A post-test zero-span calibration was performed at the end of each test. The Pegasor Mi2 device was calibrated by performing an auto-zero between tests, when possible, along with a pre and post-test calibration. PM measurements were not included in many of the tests undertaken on active construction sites, due to a combination of equipment unavailability and installation challenges.

## 2.3 Machine activity and test cycles

A variety of NRMM were tested at different locations; some of which restricted the space and scope for testing. A standard test cycle could therefore not be adopted for all machines, instead, different approaches were taken which allowed the derivation of emission factors for specific activities or power bands. This fulfilled the aim of the study, to provide emission factors for use in an emission inventory, rather than assessing performance against regulatory limit values. Machine activity was disaggregated in to cold-start (all machines were tested at the beginning of the working day and hence cold-start refers to an overnight soak period), idle (for all machines, this was noted for time periods when the operator was not doing any work and the machine was switched on), and working (individual activity is described for each machine type in Table 1).

### 2.3.1 Generator tests

Seven of the most common types of generators used by the construction sector (60, 80, 100, 125, 200, 320, and 500 kVA) were tested, according to the ISO 8178 test cycle type D2. A resistive load bank was used to load the generators to 10, 25, 50, 75, and 100% electrical power capacity; the corresponding power output (in kW) at each load for the generators was recorded. Table 1 shows the activity performed by each generator.

Generators are required to conform to Stage III-A emissions standards in London [23]; these emission standards suggest that such machines require no exhaust gas after-treatment. As of 2020, all constant speed engines (e.g. generators) are required to be at EU Stage V emission standards throughout London [27]. Emission abatement measures in the form of retrofit technology, could be considered as an alternate to Stage V engines, provided the efficacy of the abatement techniques are validated.

Retrofit equipment is required to have been tested to the relevant ISO 8178 test cycle(s) and include ongoing telemetry once installed to maintain emissions reductions [27]. Here, the efficacy of these abatement approaches was tested using a 320 kVA generator retrofitted with SCR and DPF systems separately. The generator was operated under the ISO 8178 test cycle type D2, before and after the SCR and DPF systems were fitted. Particle number was measured for both the pre-DPF and post-DPF retrofit, being consistent with the EU stage V emission standards to which these retrofitted machines aspire, rather than the EU stage III-A particle mass standard.

### 2.3.2 Off-road tests

For off-road tests, many of the machines prioritised for testing were in-service and being actively used on construction sites; it was therefore not always possible to remove them service to perform a standard test cycle. Where the machine was provided solely for testing, a standardised test cycle was undertaken, examples are provided in the supplementary information. However, on an active construction site, it was not possible to control factors such as the operators' choice of machine mode (e.g. engine speed, as they may deem it necessary to utilise a specific engine mode to perform different tasks) or time spent in idle (e.g. an excavator may spend less time idling in between frequent lorry loading operation). This did, however, make the emission tests more representative of real-world machine operation. Activities being undertaken from the machines (idling, excavating, digging, boring, dumping, lifting, trenching, material handling, pumping and travel) were identified by video during each test (where they were not defined in the standard test cycle). Cold-start and idle emissions were also measured for all machines. Table 1 shows the variety of activities performed by each NRMM.

Where available, engine activity data was recorded directly from the SAE J1939 diagnostic port using either a DAWN Mini Logger [28] (HEM Data Corporation, USA) or propriety original engine manufacturers' (OEM) data loggers. Propriety software was then used to convert this data to scaled engineering parameters.

## 2.4 Measured emission factor calculation

Where measured directly, engine power output was used to convert PEMS measured in g/h to g/kWh. The power output for the generators was recorded directly, however, 15 of the 21 tested off-road machines had no J1939 port (which is only a requirement for Stage V), and it was not possible to measure power direct from the engine. For the generators, the load applied on the engine (kW) was recorded from the control panel of the generators. This was used to calculate the ISO 8178 test cycle type D2 weighted average [29] and the emission rate (g/kWh) from the mean of three repeats at each engine load capacity.

For off-road machines, PEMS data was first disaggregated into 'cold-start', 'idle', and 'working' activities using notes and video evidence, and the defined test cycle, where available. Where on board diagnostics was available and recorded, engine power (kW) was calculated on a second by second basis using Equation 1.

$$P = \frac{2 \times \pi \times N \times \tau}{60000}$$ *Equation 1*

where,

| | | |
|---|---|---|
| $P$ | = | Power (kW) |
| $N$ | = | Engine speed (rpm) |
| $\tau$ | = | Engine torque (Nm) |

Where on board diagnostics was not available, the average power (kW) used in each of these activities was calculated from the machines where engine activity was recorded (10±5% of the rated engine power during cold-start and idle, 60±15% of the rated power when working). Activity data from the engine data loggers indicated that engines utilize, on average, 60% of their rated net power (kW), when working i.e. they have an average load factor of 0.6. Additionally, during cold-start and idle, the engines produce, on average, 10% of their rated net power i.e. the load factor is 0.1. Hence, emission factors (g/kWh) are calculated by dividing the single point (g/h) emission factors by 60% of the net rated power (kW) of each individual engine when working, and 10% of the net rated power (kW) during cold-start and idle.

## 2.5 Fleet activity-weighted average emissions

To calculate the average emissions from the fleet, engine telemetry data of 1000 machines on each of 3 days (5th December 2018, 15th January 2019 and 20th February 2019) operating in London was analysed, which was made available by the OEMs. OEM telematics recorded the time spent in each engine-operation activity bandwidth (idle, low, medium, high-power) for different types of NRMM. An example data set of engine telematics from 5 different machines of an original engine manufacturer (OEM) is shown in Table 2. Idle time and working time are calculated as a percentage of ‘engine on’ time. When the engine is switched on, telemetry data from OEMs indicate that, machines on average, spend 45% of the time idling. Idle time is classified by the OEM as engine load less than 20% of maximum available engine torque. The remaining 55% of the ‘working’ time is further split in to three categories: low (20% to 40% engine torque), medium (40% to 75% engine torque), and high (>75% engine torque) power bands. The data indicates that, machines spend very little time (<10%) in the high-power mode. The intermittent nature of these variable speed engines suggests that, the minimal time spent in the medium or high-power bands, may not be the best solution for engine efficiency, or for optimal after-treatment working conditions. Cold-start emissions were measured for most of the machines, 1% of the time is allocated to the weighting factor average. Hence, emission factors (g/kWh) are calculated by the following ‘time-weighted’ average as: cold-start (1%), idle (44%), average working activity (55%) and then aggregated to a ‘single-value’ (g/kWh).

Engine telemetry data indicates that most machines spend approximately 45% of the time idling, and hence, idle emissions cannot be neglected. Thus, measured emissions were reported on a ‘single-value’ time-weighted-activity factor (g/kWh), estimated using a weighting factor of 1% for cold-start, 44% for idle, and 55% for working emissions, shown in Table 1.

*Table 2 Example dataset of machine’s telematics data, indicating NRMM type, engine off, idle time, and working time split in to power bands.*

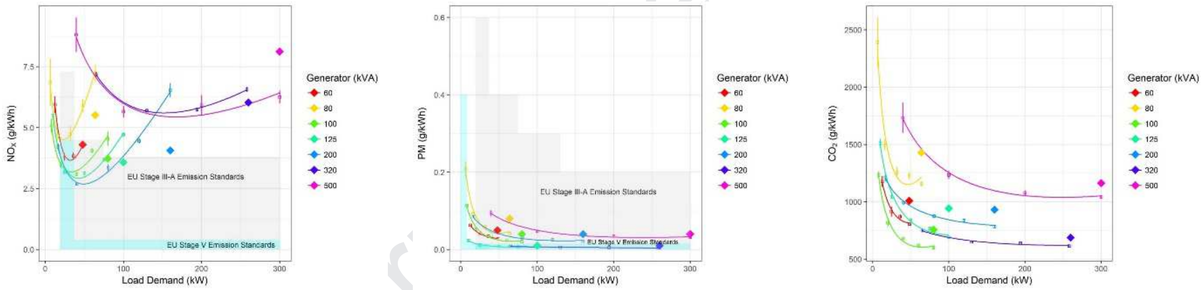
| Engine code | NRMM type | Engine off (%) | Engine on (%) | | | | |
|---|---|---|---|---|---|---|---|
| | | | Idle time | Working time | Power band (%) of working time | | |
| | | | | | low | medium | high |
| TA4i-108 | Compact wheel loaders | 92.68 | 31.51 | 68.48 | 43.58 | 22.09 | 2.80 |
| TA4-55 | Telescopic load-all | 78.26 | 71.28 | 28.71 | 20.03 | 6.58 | 2.09 |
| TA4-55 | Rough terrain fork lift | 93.14 | 29.89 | 70.10 | 63.11 | 6.92 | 0.05 |
| TA4i-93 | Wheeled excavators | 70.47 | 28.76 | 71.23 | 63.06 | 8.16 | 0 |
| TA4i-129 | Tracked excavators | 77.22 | 66.07 | 33.92 | 11.40 | 18.49 | 4.01 |

# 3 Results and Discussion

## 3.1 Generator tests

Not all measurements were available for all generators. The 60 kVA generator was not operated at 10% engine load, since the generator was unable to power the load bank at such a low load. The 500 kVA generator had extremely high exhaust flow at 100% engine load and was not operated at this high engine load. At 10% engine load, the 320 kVA generator was below the PEMS limit of detection for all species and is not reported for this load. For both the pre-SCR and post-SCR tests, the generator was not operated at 10% engine load, due to technical issues with the SCR dosing system at low exhaust temperature caused at such low engine load. When the same generator was fitted with a DPF, it was not tested at 100% engine load, since the manufacturers of the DPF system were not confident with the high backpressure caused by this load.

The variation in the $NO_X$, particle mass (PM), and $CO_2$ emissions (g/kWh) with load demand (kW), for all standard generators is shown in Figure 2; the SCR and DPF retrofit trials are shown in Figure 3. The same data is reported in supplementary information as g/kWh vs engine % load, g/h vs load demand and g/h vs engine % load. Emissions are expressed in units of g/kWh (calculated from the generator output), to compare with the respective NRMM EU emission standards (Stage III-A for generators). EU Stage V emission standards for $NO_X$, PM, and particle number (PN) is shown to compare with future regulations. Currently there is no regulation for PN emissions, for Stage III-A engines, however, PM is regulated.




(a) Generator $NO_X$ emissions (b) Generator PM emissions (c) Generator $CO_2$ emissions

*Figure 2 : $NO_X$ (g/kWh) PM, and $CO_2$ emissions (g/kWh) v/s load demand (kW). Estimated standard error bars are plotted for each measured point. 2nd order polynomial curves are applied between the points. ISO 8178 test cycle type D2 weighted average emission factor points are plotted for each generator. Stage III-A emission standards are shaded in grey and Stage V emission standards are shaded in blue, for $NO_X$ and PM.*

### 3.1.1 Generator $NO_X$ emissions

In Figure 2a, all generators follow a similar "u-shape" curve, for load applied on the engine due to the small amount of work (kW) undertaken at low loads and lean fuel burn and high engine temperature at high loads. Lowest $NO_X$ emissions were recorded for each generator between 25% and 50% engine load operation. The 60, 80, 100, 125, and 200 kVA generators complied with their respective emission standards at the 25-50% engine load. However, at low (10%) and higher loads (75-100%), these generators are above their respective emission standards. The 320 and 500 kVA generators are above their respective emission standards at all loads. The ISO 8178 test cycle type D2 weighted average emission factors for the 60 kVA, 100 kVA, and 125 kVA generators showed that these engines complied with the EU stage III-A emission standards. However, the 80, 200, 320, and 500 kVA generators were 1.25, 1.08, 1.58, and 1.46 times above their respective EU Stage III-A $NO_X$ emission standards.

### 3.1.2 Generator PM emissions

In Figure 2b, all generators show a decrease in the particulate matter emissions per kWh, with an increase in the load applied on the engine. The ISO 8178 test cycle type D2 weighted average emission factors for all generators are within their respective EU Stage III-A emission standards.

Since, EU Stage V emission standards are regulated for particle number, as well as for particle mass; a direct comparison could also be made, with respect to future standards. At the current technology level, most generators do not meet the EU Stage V emission standards for particle mass.

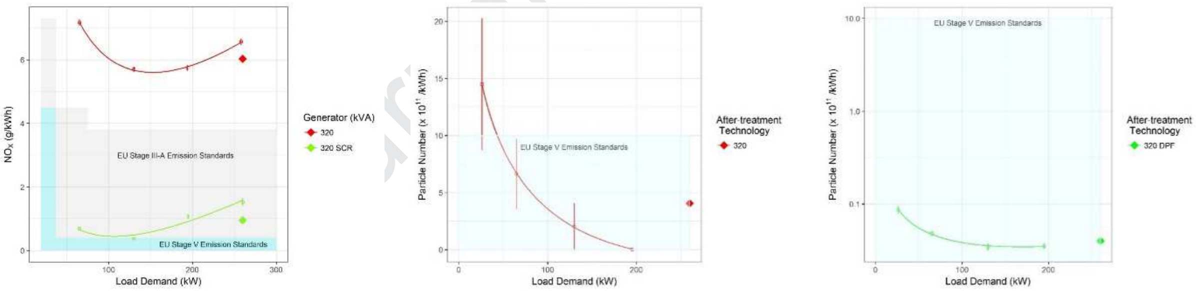
### 3.1.3 Generator CO2 emissions

In Figure 2c, all generators showed a decrease in the $CO_2$ emissions, with an increase in the load applied on the engine. Since, theoretically all the carbon in the fuel is converted to $CO_2$, the emission factors for $CO_2$ could be used to identify the fuel efficiency of each generator. The decrease in the $CO_2$ emissions corresponding with an increase in the load, suggests that all generators have a higher fuel efficiency at high loads. There is a higher rate of change in $CO_2$ emissions at 10%-50% engine load compared to 50%-100% engine load. This corresponds with the linear increase in the mass of $CO_2$ emitted (g/h) by the generators with the load demand (kW).

### 3.1.4 SCR and DPF retrofit on generators

Figure 3a shows that the SCR retrofit generator had lower $NO_X$ emissions, when compared with the pre-SCR trial, for all engine loads applied. Pre-SCR technology, the ISO 8178 test cycle type D2 weighted average $NO_X$ emission factor was 6.03 g/kWh, this reduced to 0.95 g/kWh, after SCR was fitted. However, this 85% reduction was not enough to comply with the EU Stage V emission standards.

In Figure 3b, the particle number for the pre-DPF trial is plotted on a linear y-axis. To enable the reduction in the particle number with load to be seen, the particle number for the post-DPF trial is plotted on a lognormal y-axis, shown in Figure 3c. Pre-DPF, the ISO 8178 test cycle type D2 weighted average emission factor for PN was noted at $4.06 \times 10^{11}(\text{kWh})^{-1}$, which reduces to $0.04 \times 10^{11}(\text{kWh})^{-1}$ after the DPF is used. This indicates that the DPF can reduce particle number by 2 orders of magnitude and comply with future Stage V emission standards for PN, which is $1 \times 10^{12}(\text{kWh})^{-1}$.




(a) SCR generator trial (b) pre DPF generator trial (c) post DPF generator trial

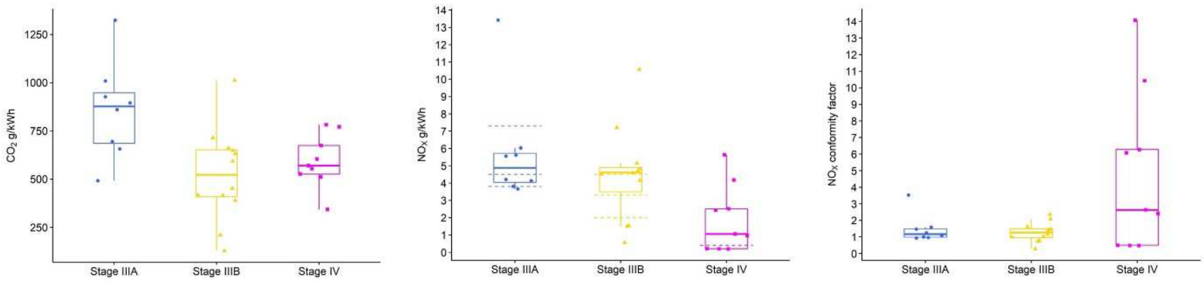
*Figure 3 $NO_X$ (g/kWh) and PN (1/kWh) emissions v/s load demand (kW). Estimated standard error bars are plotted for each measured point. 2nd order polynomial curves are applied between the points. ISO 8178 test cycle type D2 weighted average emission factor points are plotted for each generator technology.*

## 3.2 Off-road tests

A summary of the $CO_2$ and $NO_X$ emissions as g/kWh are shown in Figure 4a and Figure 4b, respectively, and as conformity factors for $NO_X$ in Figure 4c. Single point values of the emissions are plotted for each NRMM tested, calculated in accordance with corresponding fleet activity-weighted average data as described earlier. Since, the generators were tested on the ISO 8178 test cycle type D2, corresponding weighted average emission factors are plotted for each individual generator [29].

### 3.2.1 Off-road $CO_2$ emissions

$CO_2$ emissions (g/kWh) for all NRMM tested, grouped by their respective EU emission standards are shown in Figure 4a. There is a 40% average decrease in the $CO_2$ emissions between Stage III-A and III-B machines, while Stage IV machines showed a 9% average increase in $CO_2$ emissions, when compared with Stage III-B machines. Overall, Stage III-A machines emit higher $CO_2$, possibly due to the different engine management and fuel injection techniques used in these engines, compared to their newer counterparts. Details on the $CO_2$ emission factors for individual activities for each NRMM are shown in supplementary information.




(a) $CO_2$ emissions (g/kWh) (b) $NO_X$ emissions (g/kWh) (c) $NO_X$ conformity factors

*Figure 4 $CO_2$ emissions in g/kWh, $NO_X$ emissions in g/kWh and $NO_X$ conformity factors for all NRMM tested, grouped by their respective EU emission standards.*

### 3.2.2 Off-road $NO_X$ emissions

$NO_X$ emission factors (g/kWh) for all the machines tested, grouped by their respective emission standards are shown in Figure 4b, alongside the corresponding conformity factors (CF) in Figure 4c. The $NO_X$ emission standards for the different engine category codes are shown by the dashed lines across the boxplots. Each point represents a machine tested; median $NO_X$ emissions are represented by the solid horizontal line within the respective boxplot. There is a 5.5% reduction in the average emissions between Stage III-A (4.88g/kWh) and III-B (4.61g/kWh) machines; a 77% reduction in the average emission between Stage III-B and IV (1.05g/kWh) machines. Individual $NO_X$ emission factors for each of the 30 different NRMM measured is shown in supplementary information, along with the EU emission standard limit values for the different engine categories. This provides an indication of the $NO_X$ that is emitted in a real-world in-use working environment. Different engine sizes have varying limit values within an emission standard, for example, a Stage III-B engine with a rated power between 130 and 560 kW has an emission standard of 2 g/kWh for $NO_X$, while a Stage III-B engine with a rated power between 56 and 130 kW has an emission standard of 3.3 g/kWh for $NO_X$. Typically, conformity factors (CF) are used to relate the emissions measured in the Real-world Driving Emissions (RDE) test to the laboratory emissions test limit. In some instances, maximum CFs are defined [2, 21, 30], for example, a RDE conformity factor of 2.1 had been established for on-road light duty vehicles (LDVs), and 1.5 for on-road heavy duty goods vehicles (HGVs). Here, CFs are used to compare these results directly with the emissions standards and were calculated by dividing the measured $NO_X$ (g/kWh) emission factors by the corresponding EU emission standard limit values for $NO_X$ (g/kWh) for each engine emission category; these are shown in Figure 4c. However, since the machines were not measured according to a certification test cycle in this study, the conformity factors shown here are indicative of real-world operation and are not meant for compliance testing or certification purposes. 22 of 30 machines measured (~75%), had a CF lower than 2.1. Of the remaining 8 machines, 6 were Stage IV, which emitted lower overall $NO_X$ emissions (g/kWh) than Stage III-B or III-A machines with a similar net engine power.

*EU Stage III-A machines*

Eight EU Stage III-A NRMM were tested; 38% had a CF ≤1 and were found to comply with their respective emission standards. Seven of these machines were generators, and were discussed in detail, in the previous section; only three generators were compliant. The remaining Stage III-A machine tested was a 112 kW concrete pump, which had an overall $NO_X$ emission factor of 13.41 g/kWh, 3.5 times above the Stage III-A emission standard of 4 g/kWh (HC+$NO_X$) for the respective emission category.

*EU Stage III-B machines*

12 Stage III-B machines were tested; 33% had a CF ≤1 and were found to comply with their respective emission standards: 4.7 g/kWh (HC+$NO_X$) for engines rated below 56 kW, 3.3 g/kWh ($NO_X$) for engines rated between 56 and 129 kW, and 2 g/kWh ($NO_X$) for engines rated between 130 and 560 kW. These include the 49 kW excavator (4.58 g/kWh), 73 kW excavator (4.63 g/kWh), 81 kW telehandler (4.81 g/kWh), 129 kW excavator (4.70 g/kWh), 186 kW crane (1.53 g/kWh), 317 kW excavator (1.50 g/kWh), and 382 kW drilling rig (0.55 g/kWh). Those with a CF >1 included a 150 kW concrete pump (4.15 g/kWh $NO_X$) and a 55 kW rough terrain forklift (10.56 g/kWh).

Significant variability was observed between the two 55 kW rated dumpers tested. One machine equipped with a 4.4 litre engine, which was tested using a test cycle in cold snowy conditions, emitted 7.19 g/kWh of $NO_X$ (CF=1.6). The other machine had a 3.6 litre engine, was tested undertaking real world duties at an active construction site, in sunny weather, emitted 5.13 g/kWh of $NO_X$ (CF=1.16). The operator of the 4.4 litre dumper did not switch off the engine during the tests, while the operator of the 3.6 litre dumper switched off the engine intermittently during the 'dumping' period. It was surprising that these similar machines showed such different results, which may be due to the ambient conditions during testing or the operator behaviour and must be investigated further.

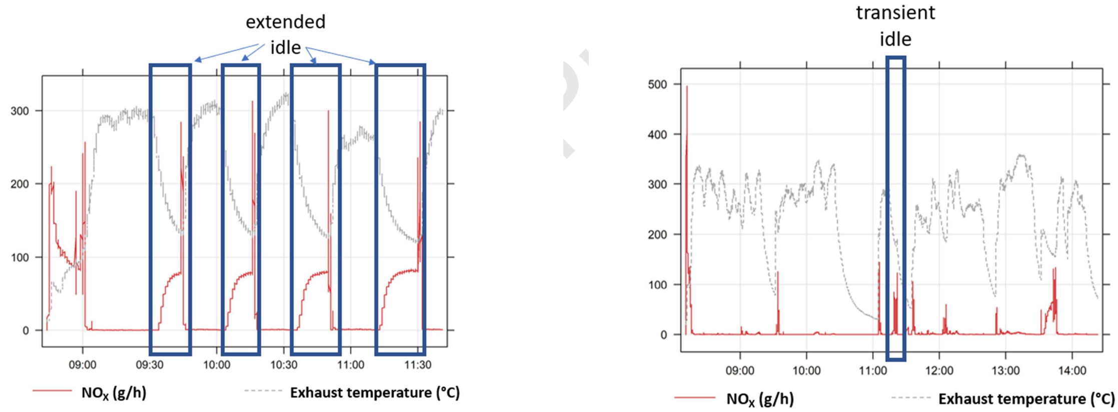
*EU Stage IV machines*

Prior to retrofitting the 320 kVA (260 kW) generator with a SCR system, the generator emitted 6.02 g/kWh of $NO_X$ (CF=1.58 corresponding to Stage III-A). With a working SCR system, the same generator emitted 0.96 g/kWh of $NO_X$ (CF=2.4 corresponding to Stage IV). During the 'working' cycle, newer machines (Stage IV) with functional SCR systems, emit up to an order of magnitude lower $NO_X$ when compared to older engines with no exhaust gas after-treatment (Stage III-A and Stage III-B), shown in Table 1. One of the 129 kW excavators, approved to engine category 'R' emitted 0.2 g/kWh of $NO_X$ (CF=0.5), the 136 kW front end loader emitted 0.19 g/kWh of $NO_X$ (CF=0.48), while the 375 kW pump emitted 0.19 g/kWh of $NO_X$ (CF=0.48). All these machines were within their Stage IV emission standard of 0.4 g/kWh.

Reductions in exhaust temperature due to idling were observed to reduce the efficacy of the SCR system, shown in Figure 5. Figure 5a shows the entire run cycle of the 129 kW excavator (rated to engine category code 'Q'), tested at an active construction site, which mainly performed the 'lorry-loading' cycle, with extended idle periods (∼15 minutes) in between each working cycle, shown by the blue boxes in Figure 5a. The exhaust temperature was above 200 °C for ∼57%, while the machine idled for ∼39% of the entire measured test. Another 129 kW excavator (rated to engine category code 'R'), was tested at a different construction site; the complete test cycle is shown in Figure 5b. This machine performed various activities, including lorry-loading, lifting, digging, and was idling for a short period of time (<10 minutes) shown in the blue box in Figure 5b. The exhaust temperature was above 200 °C for ∼70%, while the machine idled for ∼2% of the entire measured test. When the machine idles, the drop in the exhaust temperature (lines shaded in grey) corresponds with an increase in the $NO_X$ (g/h) emitted (lines shaded in red), shown in the blue boxes, in both Figure 5a and Figure 5b. The machine (Figure 5a), which idled for an extended time period, emitted higher $NO_X$ (g/h), when compared with the machine (Figure 5b), which idled for a short duration, as shown in supplementary information. The corresponding change in exhaust temperature, as recorded by the PEMS is also shown in supplementary information. During extended idle periods, the load on the engine reduces, causing a reduction in the exhaust mass flow along with a decrease in exhaust temperature. The average exhaust temperature during "extended" idle periods is ∼165 °C, well below the optimal temperature (200-250 °C) required for the SCR system to functionally dose Diesel Exhaust Fluid (DEF), which is required to convert NO/$NO_2$, and in turn reduce the overall $NO_X$ emissions [31, 32, 33, 34, 35, 36, 37, 38, 39, 40].

During transient idle period, an average exhaust temperature of 210 °C was noted, which is within the lower boundary of the SCR system to function optimally, and thus reduces $NO_X$. The 78 kW excavator emitted 2.51 g/kWh of $NO_X$ (CF=6.27), the 93 kW excavator emitted 4.17 g/kWh of $NO_X$ (CF=10.42), one of the 129 kW excavators emitted 2.43 g/kWh of NOX (CF=6.08), and the 328 kW rig emitted 1.05 g/kWh of $NO_X$ (CF=2.63). All these machines were above the emission standard of 0.4 g/kWh of $NO_X$, mainly due to the extended idle period in between their respective working cycles, allowing the SCR to properly function, without a decrease in exhaust temperature. The 93 kW telehandler emitted 5.63 g/kWh of $NO_X$, equivalent to a Stage III-B telehandler of a similar engine size (81 kW net power). This machine did not have a working exhaust gas after-treatment system, even during the 'working' cycle. Moreover, this machine did not show any warning lights on the operator's display, to give any indication of the SCR malfunction.

There are no emission standard regulations for Stage IV machines below 56 kW net engine power. Hence, machines below 56 kW net engine power are not fitted with any exhaust gas after-treatment systems like SCR, to control for $NO_X$ emissions. However, Stage V engines have significantly tighter $NO_X$ emission standards for engines with a net power above 56 kW. Results from a 55 kW prototype Stage V telehandler is also shown, which emits 4.25 g/kWh of $NO_X$. Category 'NRE-v/c-4' (rated between 37 and 55 kW engine power) of Stage V emission standards has a limit value of 4.7 g/kWh ($HC+NO_X$), hence, this telehandler is within the emission standard. The succeeding category 'NRE-v/c-5' (rated between 56 and 129 kW engine power) of Stage V has a limit value of 0.4 g/kWh, requiring machines of this category to have an exhaust gas after-treatment system fitted to it, to control for $NO_X$ emissions.




(a) Machine activity during an extended idle work cycle.

(b) Machine activity during a transient idle work cycle.

*Figure 5 Time spent idling by two machines during their respective workday activity cycles.*

# 4 Conclusions

The main aim of this research was to measure the emissions from the most commonly used construction machines in London during real world operation as they form an important subset of emissions in London, where policy interventions are being actively formulated. Other types of NRMM for example transport refrigeration units, garden and hand-held machines, snowmobiles, machines used at waste transfer stations were not included here. 29 construction machines were tested using PEMS, representing Stage III-A, III-B, and IV NRMM emission standards, while $NO_X$ emissions from one Stage V prototype machine, tested by an OEM is shown.

Emissions of $NO_X$ and particles (both particle matter and particle number) were measured in g/h and converted to g/kWh using the power output from the engine where available. For some of the engines, this was derived from the power output of similar machines undertaking the same work, as no J1939 port was available for the direct logging of the engine activity. This is a barrier to assessing the emissions of these older engines. 'In-service monitoring' of future European Stage V non-road machines requires the machines to have J1939 diagnostic port connection capability. This would improve the activity data logging capability, which in turn would facilitate direct and easier PEMS connection to the J1939 engine diagnostic port and provide more accurate emission factors.

The highest $NO_X$ emissions (g/kWh) were from the older engines (Stage III-A and III-B), these were reduced in the newer (Stage IV) engines due to more advanced engine management systems and exhaust after treatment. The importance of SCR in reaching and maintaining the low $NO_X$ emission standards required of larger machines at Stage IV and above, was illustrated during the testing of a Stage IV telehandler. The failure of this SCR was only detectable using PEMS as no warning was given by the machine and $NO_X$ emissions were similar to a Stage III-B engine. Improved exhaust after treatment is required to ensure that the benefits of SCR are delivered in real world operation. The SCR systems were also shown to perform poorly during idling periods over approximately 10 minutes, where exhaust temperatures dropped below ~200 °C. This has important consequences for how machines are operated on active construction sites, where they are often left to idle, as well as how in-service testing protocols are developed for Stage V. It is important that future assessments of construction activity emissions consider the implications of long idling times and that manufacturers engineer solutions to maintain the SCR at operating temperature or that operators adjust their working behaviour to reduce emissions.

When compared to the EU emission $NO_X$ limit values, which are stricter for newer engines, among those NRMM tested here, many (63% Stage III-A, 67% Stage III-B, 67% Stage IV) emitted more than allowed (CF >1). When compared to the in-use CF stipulated by RDE testing regulations for on-road LDVs (2.1), the NRMM PEMS tests showed that majority (73%) were within this benchmark. Particle PEMS were undertaken only on generators, which showed that all the generators were within their emission PM limit values, at all loads. For the generator retrofitted with DPF after-treatment technology, an overall reduction of 2 orders of magnitude for PN was observed.

Although there are no emission standards for $CO_2$, the emission factors measured in this study can be used to assess the benefits of current policies to accelerate the uptake of higher emission standard engines into the London fleet.

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**Competing interests**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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**Declaration of interests**

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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